

Final report for:

GRANT No. NASA/NCC3-466

GRANT TITLE: **Fundamental Processes of Atomization in fluid-fluid flows**

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PIs: M. J. McCready, H. -C. Chang and D. T. Leighton
University of Notre Dame

1. Major results

The details on each of these topics were given in the regular progress reports and are available in the papers. Here we list the major results achieved and the significance.

- i. We have shown that atomization in liquid/liquid shear flow is driven by a *viscous shear instability* that triggers the formation of a long thin sheet (Roberts et al., 1998). Experiments show that breakup of the sheets occurs by kinematic stretching and is not consistent with a second, (e.g., capillary) instability. These new results provide insight into both the expected rate of atomization and the size of the drops that would be formed. Further we found that atomization will effectively not occur in oscillatory shear situations (King et. al., 1999).
- ii. We discovered a new mode of interfacial instability for *oscillatory* two-layer systems (King et al., 1999) whereby a mode that originates within the less viscous liquid phase causes interfacial deformation as the oscillation proceeds. This is significant because most multiphase flows are not really steady. Various flow transients can be often be successfully modeled with oscillatory theories. Recognition of a different instability mechanism for transients could change how flow regime transitions are viewed.
- iii. We have shown that rivulet formation from a gravity front occurs because the local front shape specified by gravity and surface tension changes from a nose to a wedge geometry, thus triggering a large increase in viscous resistance (Veretennikov et al., 1998),
- iv. We extended our studies on nonlinear wave evolution on falling films and in stratified flow, particularly the evolution towards large-amplitude solitary waves that tend to generate drops. A book on falling film dynamics was written during this time. We showed that the monochromatic waves at inception suffer a unique modulation instability that produces jumps in the average wave-induced flow rate and thickness. Such jumps cause liquid drainage towards them to produce solitary waves rapidly. We determine how these solitary waves grow and interact with the monochromatic wave field. We also studied how these solitary waves significantly enhance interfacial mass transfer because of the presence of large vortices beneath their crests. (Chang et al., 1998; , Chang et al, 1997; Chang et al, 1999; Roberts et al, 2000a; Roberts and Chang, 2000; Chang et al, 2000).

2. Publications

C. T. Gallagher, M. J. McCready and D. T. Leighton, Experimental investigation of a two-layer shearing instability in a cylindrical Couette cell", *Phys. Fluids*, 8, 2385-2392, 1996.

H. -C. Chang, E. A. Demekhin and E. Kalaidin, Scalings, Self-Similarity and Statistics of Interfacial Turbulence on a Falling Film, pp. 86-111 Advances in Multi-Fluid Flows, eds. Renardy, Coward, Papageorgiou and Sun, SIAM (1996).

H. -C. Chang, E. A. Demekhin, E. Kalaidin and Y. Ye, "Nonlinear wavenumber selection in gradient flow systems", *Phys. Rev. E*, 55 2818 (1997).

M. Sangalli, M. J. McCready and H. -C. Chang, "Stabilization mechanisms of short waves in gas-liquid flow", *Phys. Fluids*, 9, pp. 919-939, (1997).

Indeikina, A., Veretennikov, I. and Chang, H.-C., "Drop Falloff from Pendent Rivulets", *J. Fluid Mech.*, 338, 173-201 (1997).

Veretennikov, I., Indeikina, A. and Chang, H.-C., "Front Dynamics and Fingering of a Driven Contact Line", *J. Fluid Mech.*, 373, 81 (1998).

Roberts, R. Chang, H.-C., Leighton, D. T., McCready, M. J. , Mechanism of atomization in a two-layer Couette flow, proceedings of fourth Microgravity Fluid Dynamics Conference, Cleveland, August, (1998).

I. Veretennikov, A., Agarwal, A., Indeikina and H-C Chang, Unusual Contact-line Dynamics of Thick Films and Drops, *J. Colloid and Interface Sci*, 215, 425(1999).

M. J. McCready, "Spatial evolution of interfacial waves in gas-liquid flows", in *Fluid Dynamics at Interfaces*, Ed Shyy and Narayanan, pp129-141, 1999.

Chang, H.-C., Demekhin, E. A., Roberts, R. M. and Ye, Y., "Modulation Wave Dynamics of Kinematic Interfacial Waves" pages 99-112 in "Fluid Dynamics at Interfaces", Editors: W. Shyy and R. Narayanan, Cambridge(1999).

H-C. Chang, E. A. Demekhin and E. Kalaidin, Iterated Stretching of Viscoelastic Jets, *Phys of Fluids*, 11, 1717(1999).

M. R. King. D. T. Leighton and M. J. McCready, "Stability of oscillatory two-phase Couette Flow: theory and experiment", *Phys. Fluids*, 11, 833-844 1999.

Ye Y. and Chang, H.-C., "A Spectral Theory for Fingering on a Prewetted Plane", *Physics of Fluids*, 11, 2494 (1999).

M. R. King and M. J. McCready, "Weakly nonlinear simulation of planar stratified flows", *Physics of Fluids*, 12, 92-102, 2000.

R. M. Roberts & H. C. Chang, "Wave-enhanced interfacial transfer", *Chemical Engineering Science*, 55, 1127-1141, 2000

Robert, R. M., Ye, Y., Demekhin, E. A and Chang, H.-C., "Wave Dynamics in Two-Layer Couette Flow", *Chemical Engineering Science*, 55, 345 2000a.

M. J. McCready, M. R. King and B. D. Woods, "Weakly-nonlinear waves in two-layer flows: Subcritical bifurcations", in *Nonlinear waves in multi-phase flows*, Ed. H. -C. Chang, pp 81-92, 2000.

R. M. Roberts, Y Ye, E. A. Demekhin & H. C. Chang "Wave dynamics in two-layer Couette flow", *Chemical Engineering Science*, 55: (2) 345-362, Sp. Iss. SI JAN 2000b.

Chang, H.-C., Demekhin, E. A. and Kalaidin, E., "Coherent Structures, Self-Similarity, and Universal Roll Wave Coarsening Dynamics", *Phys. of Fluids*, 12, 2268 (2000).

Chang, H.-C., Demekhin, E. A. and Takhistov, P. V., "Circular Hydraulic Jumps Triggered by Boundary Layer Separation", *Journal of Colloid and Interface Science*, 233, 329(2001).

Book: "Complex Wave Dynamics on Falling Films", H.-C. Chang and E. A. Demekhin, Elsevier Press (in press).

Presentations at meetings:

M. R. King, D. T. Leighton and M. J. McCready, "Stability of Oscillatory Two-Phase Couette Flow: Theory and Experiment", AIChE Meeting, Los Angeles, November, 1997.

M. R. King, D. T. Leighton and M. J. McCready, Mechanism for Interfacial Wave Growth in a Stratified, Oscillatory Shear Flow" AIChE, Fall Meeting November, 1998.

M. J. McCready, " Interfacial waves in steady and oscillatory, two-layer Couette flows" Symposium to honor Professor Thomas J. Hanratty, University of Illinois, Urbana, May, 1998

M. R. King and M. J. McCready, Nonlinear simulation of interfacial waves in a planar flow" AIChE, Fall Meeting November, 1999.

B. D. Woods and M. J. McCready, Behavior of Interfacial Waves in Cocurrent Oil-Water Channel Flow, APS 1999

M. J. McCready, "Mechanisms of Atomization", presented at: Annual meeting of the Institute for Multifluid Flows, March 2000.

M. J. McCready, R. Roberts, D. T. Leighton and H. -C. Chang "Mechanism of atomization in a two-layer Couette flow", Fourth Microgravity Fluid Dynamics Conference, Cleveland, August, 1998.

M. J. McCready, B. D. Woods, "Atomization Processes in Fluid-Fluid Flows: Prediction of the Frequency of the Precursor Solitary Waves", Fifth Microgravity Fluid Dynamics Conference, Cleveland, August, 2000.

B. D. Woods, M. J. McCready, "Role of Secondary Instabilities Upon Flow Development in Gas-Liquid Flows", Fifth Microgravity Fluid Dynamics Conference, AIChE, Fall Meeting November, 2000.

4. Invited lectures/seminars

M. J. McCready, "Formation and evolution of interfacial waves in multifluid flows", Mechanical Engineering Heat Transfer Group, Purdue University, April 24, 1997.

M. J. McCready, "Interfacial waves in steady and oscillatory, two-layer Couette flows", Virginia Tech, Department of Mathematics, September 18, 1998.

M. J. McCready, "Interfacial behavior and reaction outcome in multifluid flows ", Dow Chemical Co., Midland Michigan, August, 1999.

M. J. McCready, "Interfacial waves caused by flow oscillations with applications to transient flows and noisy pumps", Sixth US-Japan seminar on two-phase flow dynamics, Santa Barbara, CA, June 2000.

5. Total degrees granted. (includes partial support for some)

Ph.D. degrees.

Christopher T. Gallagher, "Experimental investigation of a two-layer shearing instability" --Ph. D., 1996 (McCready & Leighton)

Randy Roberts, "Interfacial Wave Behavior and Mass Transfer of Multi-Fluid Flows", 1998. (Chang and McCready)

Donald Uphold, "Linear stability of multifluid flows" -- Ph. D. 1997 (M. J. McCready)

Ye Yi, "Instabilities of thin film waves and fronts" -- Ph. D. 1998 (H. -C. Chang)

Michael R. King, "Interfacial dynamics of oscillatory flows" – Ph. D.1999 (McCready and Leighton)

M.S. degrees. (all directed by M. J. McCready)

Xiaohong Wang, "Numerical simulation of stratified flow", --MS-2000

6. Post Doctoral Fellows

Benjamin Woods, 2001 -- Now with Exxon/Mobil production research.